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Analysis of Advanced Programs (Study 2.3) Final Report

Volume I. Executive Summary

Prepared by
ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

August 1972

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASw-2301

Systems Engineering Operations
THE AEROSPACE CORPORATION

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(STUDY 2.3)

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Approved:

L. R. Sitney Associate Group Director Advanced Vehicle Systems Directorate Systems Planning Division	S. M. Tennant Associate General Manager Systems Planning Division Systems Engineering Operations

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I. INTRODUCTION

This report provides an Executive Summary of the activities which comprised Study 2.3, "Analysis of Advanced Programs," of NASA Contract NASw-2301. The study originally consisted of three separate subtasks primarily related to the Space Shuttle,

2.3.1 - Vehicle Data Reference Base
2.3.2 - Advanced STS Program Analysis
2.3.3 - Advanced Development Analysis

Subtask 2.3.4, "Utilization of Solid Rocket Motors (SRMs) for Space Shuttle," was added to the contract on 15 May 1972 to provide SRM data to the Marshall Space Flight Center (MSFC). A concise description of each significant activity accomplished under Study 2.3 is included in this executive summary. More detailed descriptions are contained in Volume II, "Study Results," of the Study 2.3 Final Report, Aerospace Technical Report No. ATR-73(7313-01)-1, (Reference 1) and in the documentation developed during the conduct of Study 2.3 as listed in Table 1 and in References 1 - 6.

The period of performance of Study 2.3 was from 1 October 1971 to 31 August 1972, with the exception of Subtask 2.3.4 which ran only from mid-May to the end of August. Approximately 48.9 man months were expended by Members of the Technical Staff (MTS) on the first three subtasks and 50.0 man months on Subtask 2.3.4.

During the first six months of the Study, major emphasis on the first three subtasks was placed on the analysis of alternate Space Shuttle configurations, including technical issues, performance, and costs. Once the Request for Proposal for the NASA Phase C Shuttle contract was issued in mid-March, emphasis shifted from vehicle-oriented analyses to additional costing effort in the areas of body/tank structure and aerodynamic surfaces cost estimating relationships (CERs) and to a new activity to develop additional cost data for large solid rocket motors. A continuing effort at the level of approximately one MTS each was expended in support of the Advanced Development Office (MTG) of the Advanced Missions Directorate, and in support of Manned Spacecraft Center (MSC) Shuttle costing analyses through the use of the Aerospace Vehicle Synthesis Program. At the end of June a very small pilot effort was initiated in support of in-house NASA activities to develop a program model combining performance and cost factors applicable to NASA space programs.

Table I-1. Study 2.3 Documentation*

TITLE	REPORT NUMBER
Analysis of Advanced Programs (Study 2.3) Final Report - Executive Summary	ATR-73(7313-01)-1 Volume I
Analysis of Advanced Programs (Study 2.3) Final Report - Study Results	ATR-73(7313-01)-1 Volume II
Analysis of Advanced Programs (Study 2.3) Final Report - Study Results - Utilization of Solid Rocket Motors for Space Shuttle	ATR-73(7313-01)-1 Volume II Appendix A
Body/Tank Structure CER Review	ATR-73(7313-01)-2
Aerodynamic Surface CER Review	ATR-73(7313-01)-3
Solid Rocket Motor Cost Model	ATR-73(7313-01)-4
Aerospace Vehicle Synthesis Program (Study 2.3.1)	ATR-73(7313-01)-5
Utilization of Solid Rocket Motors for Space Shuttle - Structural Design Criteria of SRM Case for Space Shuttle - Study 2.3.4	ATR-73(7313-02)-1 Volume I
Utilization of Solid Rocket Motors for Space Shuttle - Proof Factors and Design Factors of Safety for a Reusable SRM Case - Study 2.3.4	ATR-73(7313-02)-1 Volume II
Utilization of Solid Rocket Motors for Space Shuttle - Materials Review of SRM Case Fabrication - Study 2.3.4	ATR-73(7313-02)-1 Volume III
Utilization of Solid Rocket Motors for Space Shuttle - SRM Thrust Negation Response Analysis for Space Shuttle - Study 2.3.4	ATR-73(7313-02)-1 Volume IV
Utilization of Solid Rocket Motors for Space Shuttle - Analysis of Thrust Transients During Thrust Negation - Study 2.3.4	ATR-73(7313-02)-1 Volume V
Utilization of Solid Rocket Motors for Space Shuttle - SRM Vendor Survey - Study 2.3.4	ATR-73(7313-02)-1 Volume VI
Utilization of Solid Rocket Motors for Space Shuttle - Staging Motor Exhaust-Plume Effects on Shuttle Vehicle - Study 2.3.4	ATR-73(7313-02)-1 Volume VII
Utilization of Solid Rocket Motors for Space Shuttle - Recovery System Concept for SRM - Study 2.3.4	ATR-73(7313-02)-1 Volume VIII
Utilization of Solid Rocket Motors for Space Shuttle - SRM Internal Ballistics and Nozzle Designs - Study 2.3.4	ATR-73(7313-02)-1 Volume IX
ELDO Tug Phase B Cost Estimate (letter)	72-2810K-026
Traffic Accommodation Analysis (letter)	72-2810-REK-61

* All reports are to be published in September 1972.

II. STUDY OBJECTIVES

The overall objective of Study 2.3 was to provide inputs to the Director of Advanced Programs (MT) to assist NASA in arriving at programmatic decisions. In general, these studies supplemented in-house NASA studies in the same areas and provided additional data to NASA to be used in reaching conclusions on various issues of concern to NASA at the time the studies were performed.

The principal objectives of the first three subtasks* were to:

1. Maintain a data bank which related vehicle description, performance, cost, and technical risk for configurations under review.
2. Update and refine computer programs and methodology used to estimate program cost implications of space vehicle program uncertainties.
3. Analyze relative effectiveness of advanced STS programs identified by NASA.
4. Suggest potential benefits which might be gained either through novel and imaginative application of vehicle configurations currently under study or through development of new vehicle configurations.
5. Advise the Technical Director of the need for any study changes or additional studies related to NASA Phase B Space Shuttle effort.
6. Identify new concepts and techniques which could significantly influence advanced mission capabilities.
7. Develop and maintain a descriptive catalog of the identified development requirements.

The principal objectives of Subtask 2.3.4 were to:

1. Convey to NASA the USAF/Aerospace experience in large solid rocket motor development.
2. Apply this experience to specific analysis tasks for the Shuttle SRMs.
3. Provide, whenever possible, parametric data on SRM designs which have applicability to analyses being performed by NASA.

* The basic Statement of Work for Study 2.3 is included as Appendix A to this report.

III. RELATIONSHIP TO OTHER NASA EFFORTS

To accomplish the overall and specific objectives of Study 2.3, close coordination was maintained with both NASA and DOD Space Shuttle activities. In addition, Government and contractor efforts on other elements, e.g., Space Tug, of the Space Transportation System (STS) were followed, but only to the extent necessary to provide current data as needed in support of Study 2.3.

There was a close interaction between Study 2.3 and Study 2.5, "Advanced Program Operations/Logistics Analyses," during the course of Contract NASw-2301 in that Study 2.3 provided vehicle data to Study 2.5 for DORCA analyses. Interaction also took place to a lesser degree with Study 2.4, "Analysis of Space Tug Operation Techniques," primarily in the transfer of ELDO-related Tug data to Study 2.3. Interplay with the other three studies covered by this contract was not substantial, due to the limited overlap in the scope of the other three studies with Study 2.3.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

As indicated in the Introduction, Study 2.3 consisted of four subtasks:

- 2.3.1 - Vehicle Data Reference Base
- 2.3.2 - Advanced STS Program Analysis
- 2.3.3 - Advanced Development Analysis
- 2.3.4 - Utilization of Solid Rocket Motors for Space Shuttle

Emphasis on Subtask 2.3.1 was to update and refine computer programs and methodology used to estimate program cost implications of space vehicle program uncertainties. The two areas specifically worked during the Study were the Aerospace Vehicle Synthesis Program and certain of The Aerospace Corporation cost estimating relationships (CERs) used with the Aerospace STS Cost Methodology (Reference 2). The Vehicle Synthesis Program was updated as necessary, to reflect the various Shuttle configurations which were of interest to NASA MSC during the evolution of the Space Shuttle baseline during the first half of the contract period. The utility of the Program to MSC was first improved by modifying its format to be more compatible with the MSC cost format. The Program was subsequently modified to incorporate dummy MSC CERs so that MSC could generate configuration-dependent Shuttle cost data directly. In the cost area, the Body/Tank Structure CER and the Aerodynamic Surfaces CER were reanalyzed using new NASA cost data for the Saturn stages and new data on military aircraft, respectively.

Subtask 2.3.2 was intended to provide data to the Office of Manned Space Flight on the relative effectiveness of advanced STS programs of interest to NASA; in accomplishing this goal, maximum use was made of data developed in Subtask 2.3.1. For the most part, with the exception of the IDA Minimum Spacecraft analysis, these analyses were limited to the NASA Phase B Shuttle configurations and concentrated primarily on various technical and economic factors which could have an impact on Shuttle program decisions by the NASA. In general, this subtask was used by the NASA Program Director (MT) to develop ad hoc data to assist NASA in its decision-making on the Shuttle program.

In Subtask 2.3.3, The Aerospace Corporation used its insight into NASA, DOD, and in-house studies to identify new concepts and techniques which could significantly influence advanced mission capabilities. Since this activity was to concentrate on "space systems," rather than on specific space elements, most of the concepts or techniques identified in this subtask were of a general nature and could be applied to a variety of space systems. The data developed in this subtask were submitted to the Advanced Development Office (MTS) in a Research and Technology Operating Plans (RTOP)-compatible format to provide maximum benefit to budgetary planning activities within NASA.

Subtask 2.3.4 made use of Aerospace's experience with large solid rocket motor development programs to provide useful data and analyses to MSFC in support of its role as the program manager for the Shuttle SRM booster program. Past Aerospace, contractor and Air Force data from the Titan III and 156 in. SRM programs were reviewed and pertinent data were extracted to provide a point of departure for Aerospace Shuttle-related SRM analyses such as performance, dynamics, materials selection, and recovery. To the extent possible, these data were developed parametrically to have maximum utility to MSFC.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

A. SUBTASK 2.3.1 - VEHICLE DATA REFERENCE BASE

1. COST MODEL IMPROVEMENT ACTIVITIES

a. General

The cost model improvement activity was requested by NASA to correct deficiencies in The Aerospace Corporation STS Cost Methodology (Reference 2) which was widely available at the start of the contract period. These deficiencies had arisen either because newer data had made certain CERs suspect or because cost model changes were required due to changes in the Shuttle concept, e.g., solid rocket motor (SRM) boosters instead of flyback boosters. It was hoped that the improvement in The Aerospace Corporation STS Cost Methodology would provide useful cost data on the STS program. The high priority, key cost model improvement activities were the completion of the Body/Tank Structure CER Review and the development of a current SRM Cost Model. Incorporation of these two cost model improvements will update the STS Cost Methodology to the point that it will be applicable to the current Shuttle configuration. Although not reported in this section, cost support was also provided in connection with the vehicle configuration assessment activities discussed under Subtask 2.3.2.

b. Body/Tank Structure CER Review

This report (Reference 3) revised the Body/Tank Structure CER to make use of new Saturn stage cost data which became available after the original CER was developed in 1970. The new CER for DDT&E costs indicated that the costs were independent of propellant type (cryogenic or storable) whereas the original CER varied with propellant type. The new CER for theoretical first unit (TFU) cost was still a function of propellant type. The Aerospace DDT&E costs for Body/Tank Structure are reduced 40% with the new CER but TFU costs increased by 3%. Drop tank and Tug DDT&E costs will also be decreased based on the new CER.

c. SRM Cost Model

This report (Reference 4) provided NASA with an additional data source for SRM costs for the Shuttle. CERs were developed for the DDT&E, investment, and operations phases of a large SRM suitable for the Shuttle. The CERs were broken out according to the work breakdown structure (WBS) used in The Aerospace Corporation STS Cost Methodology. The major cost item in the DDT&E phase of the SRM program is test hardware since this phase is essentially a demonstration program to qualify the booster. The key component in the first unit CERs is the case plus insulation at a cost of approximately $10/lb. Propellant is estimated to cost $0.34/lb.

d. Aerodynamic Surfaces CER Review

This activity was performed to update the airframe cost data points, review the methodology, and revise the Aerodynamic Surface CER. The review indicated that no change was necessary in this CER.

e. Solid Rocket Motor Sizing Program Review

The cost subroutine of an existing Aerospace large SRM sizing program was examined and exercised by the direction of the Technical Director at the request of MSFC to estimate the SRM program costs and to test its applicability. The program was developed in the 1960s and consists of performance, weight, and costing subroutines. The general conclusion drawn from this examination was that the program's applicability to estimate current SRM program costs is uncertain because the price index for key SRM items is unknown. In addition, the program does not accommodate large production rate effects for propellants.

f. Attitude Reference System Study

This study was initiated at the end of June at the request of the Study 2.3 NASA Technical Director as a precursor to proposed FY 73 Aerospace Corporation cost performance activities. It was intended to investigate the problem and determine the weaknesses in the present data base to support the approaches to be used in FY 73. The study covers only attitude reference systems as a small part of the attitude control system. A brief attempt was made to establish a relationship between system cost and some system characteristics. Data has been compiled on seven gimbaled platforms and eight strapdown stabilization units. It has been found particularly difficult to obtain accurate information on cost and reliability and to correlate these with a single system variable.

2. VEHICLE SYNTEHSIS MODEL

Support was provided to the MSC Shuttle costing activity by conducting Shuttle performance sensitivity analyses. Efforts were also made to install the program at MSC for use by NASA personnel. A Program User's Manual (Reference 5) was prepared, and the content of the program was expanded and clarified. Cost routines were incorporated to permit the program to be more directly usable by NASA personnel.

B. SUBTASK 2.3.2 - ADVANCED STS PROGRAM ANALYSIS

1. GENERAL

A series of Shuttle studies were performed utilizing a comprehensive vehicle data bank, which was developed and updated from continuing contractor effort during the NASA Phase B Shuttle Definition phases as well as from data developed under Subtask 2.3.1. These studies were all performed prior to the 17 March release of the Phase C RFP which baselined the parallel burn SRM configuration. In most cases, the vehicles utilized in the assessment activity were predecessors of the RFP baseline which was finally selected. Some of the later efforts did include the eventual baseline system as an alternate. The conclusions which were developed at the time of the study were not revised or reevaluated following the release of the NASA RFP.

2. IDA MINIMUM SPACECRAFT SHUTTLE CONCEPT REVIEW

At the October 1971 meeting of the President's Scientific Advisory Committee (PSAC) Space Shuttle Panel, representatives of the Institute for Defense Analyses (IDA) presented a "minimum-spacecraft"

Shuttle concept which consisted of a reusable first stage, an expendable second stage, and an optional manned spacecraft/glider for use on manned missions. Promulgation of this concept was motivated by the consideration that, if payload retrieval should not prove to be of significant economic advantage, use of an unmanned vehicle configuration with an expendable upper stage may be preferred for payload deployment. The manned spacecraft/glider would be reserved for use on flights requiring manned capability. In view of the attractiveness of the performance capabilities and costs, both non-recurring and recurring, attributed to the concept by IDA, The Aerospace Corporation was directed by the NASA Study 2.3 Technical Director to conduct an independent review to substantiate IDA data or to develop an alternative set of estimates. The results of this review, were presented at the November 1971 meeting of the PSAC Space Shuttle Panel.

The following conclusions were reached:

a. Total vehicle size is sensitive to spacecraft and second stage weight, with the second stage structure factor being a key driver.

b. For equal design mission payload capability, vehicle weights derived using the Aerospace weight synthesis methodology are substantially higher (~71% GLOW) than those derived through use of the IDA weight estimating methodology.

c. Both the IDA and Aerospace vehicle configurations capture all NASA missions; use of the Centaur stage with the IDA vehicle is higher than with the Aerospace vehicle.

d. IDA and Aerospace costs estimates for the same vehicle configuration are comparable.

e. Use of Aerospace weight synthesis techniques leads to large cost differences.

f. Utility of concept, based upon Aerospace cost and weight estimating techniques, is extremely marginal.

3. SHUTTLE CONCEPT STAGING VELOCITY STUDY

Various Space Shuttle concepts were under active investigation during the early months of the extended Phase B studies. Often these concepts were defined according to different ground rules, optimized against different parameters, and, in general, could not be compared with each other on a consistent basis. In order to correct this deficiency, a study was undertaken to investigate three candidate Space Shuttle configurations on a consistent basis. The objectives of the study were to determine the "cost optimum" staging velocity for each concept and compare costs and other characteristics of the "optimized" candidate systems.

The three candidate Shuttle concepts all consisted of a LO_2/RP 1-fueled, heat sink, reusable flyback booster and a reusable orbiter which met Level 1 payload requirements with 650 fps of on-orbit ΔV remaining for each of four booster staging velocities ranging from 5,000 to 8,000 fps. The three orbiter concepts differed in the location and type of propellant tank, i.e., single end-loaded LH_2/LO_2 drop tank, twin LH_2 drop tanks, and internal tank. Both GLOW and dry weight are lower for the drop tank Shuttle systems than for the internal tank orbiter at all staging velocities, and the minimum value of these weight parameters occurs at a lower staging velocity for the drop tank systems. The variations of cost and weight with staging velocity are significantly different for the three Shuttle concepts. Staging velocity for minimum cost is considerably higher than that for minimum weight. In general, weight is a minimum at the lowest staging velocity, while cost is a minimum at the highest staging velocity, based on the STS Cost Methodology (Reference 2).

4. INTACT ABORT SENSITIVITY STUDY

During the same period that the Shuttle staging velocity sensitivity study was being performed, the intact abort issue involving the associated gaps and possible closure options became a program concern. It was also noted that staging velocity variation could be a possible closure option, especially for the downrange landing gap case, which occurred approximately 240 sec following lift-off. Therefore, it was recommended to the Study 2.3 Technical Director that the staging velocity study be extended in scope to include abort considerations for the then newly defined series and parallel burn Shuttle configurations. The study concluded that the abort gap can be eliminated by means of increasing the emergency power level of the orbiter engines (or increasing the normal thrust level) or, possibly, by increasing the staging velocity. The latter appears to be undesirable in view of the associated increase in vehicle gross weight.

5. PHASE B EXTERNAL LH_2 TANK SHUTTLE COST COMPARISON

A comparative cost analysis of the series and parallel burn Shuttle configurations studied respectively by Grumman/Boeing and McDonnell Douglas was performed to provide an understanding of costs and to identify areas of major differences. The vehicle configuration considered in this study, which was performed as part of the Shuttle Configuration Assessment Task, was the external LH_2 drop tank orbiter combined with the heat sink booster. On a total program basis, the Aerospace cost estimates are as much as 40% and 22% higher than those of G/B and MDAC, respectively.

6. PRESSURE-FED BOOSTER CONFIGURATION ASSESSMENT

The Pressure-Fed Booster (PFB) was a serious Shuttle system candidate during the early phases of the Phase B study extension. However, certain questions were raised regarding the technical feasibility, operational practicality, and economic attractiveness of this recoverable booster concept. A study was undertaken in response to those concerns to: (1) review the available data and assess the technical, operational, and economic aspects of the pressure-fed booster concept and (2) to identify PFB design problems and areas of technical concern. In this study, PFB design, operational, and performance characteristics were determined; design feasibility was assessed; and concept costs were analyzed and compared with those of other Shuttle candidates. Both series and parallel burn operating modes were considered. Based on the results of this study, it was concluded that the pressure-fed booster, in either the series or parallel burn mode, is technically feasible. The areas of technical concern do not pose any insurmountable problems. However, higher RDT&E and direct operating costs for the pressure-fed booster than estimated could easily result from solutions to booster-related design and operational problems and could reduce the attractiveness of this concept.

7. SHUTTLE CONFIGURATION ASSESSMENT

During the first half of this contract, significant effort was expended to provide data to support NASA Headquarters in the examination and evaluation of alternate Space Shuttle concepts. In most cases, these study activities were quick reaction in nature and, of necessity, took maximum advantage of existing analytical tools and available vehicle and programmatic data. One of the more important of these rapid assessment studies was performed on the four candidate Space Shuttle vehicles defined by NASA Headquarters in its TWX of 5 January 1972. Study activities were initiated upon receipt of the TWX, and results were presented to the NASA Technical Director on 19 January. The Phase B Shuttle contractor activities were closely monitored subsequent to the 5 January 1972 contract redirection, and the results of the study were continually modified and updated. Summary assessment and evaluation data addressing key issues and critical areas of the candidate Space Shuttles were provided to NASA Headquarters for use in the 25 February 1972 STS Committee Meeting.

In summary, the results of this February assessment showed that the orbiter with a smaller payload capability and bay size was not significantly cheaper than the baseline orbiter and probably would be proven not to be cost-effective from the payload/mission capture viewpoint. Conclusions with respect to the Shuttle booster are not as clear. The SRM booster offers the lowest RDT&E cost and provides the highest confidence of achieving a Shuttle system within the established cost constraints. If development cost is the critical parameter, then the SRM booster must be selected in preference to the liquid boosters; however, the liquid systems offer lower direct operating and total program costs. The SRM booster must be recovered and reused in order to be cost competitive with the liquid systems. From a cost standpoint, the series and parallel burn configurations are nearly comparable. Taking other considerations into account, the less complex series burn configuration would be preferred for the liquid systems and the lighter parallel burn configuration for the SRM booster Shuttle.

8. ORBITER DROP TANK WEIGHT VARIATION EFFECTS

Examination of Shuttle weight data as reported by the three NASA Phase B Contractors indicated wide variations in the weights of the various configurations. One of the orbiter components with a large variation in its reported weight is the expendable liquid hydrogen/liquid oxygen tank. Since this expendable tank is a large contributor to both system weight and recurring cost, a study was undertaken to review the contractors' weight estimates of this component and to determine the trends and sensitivity of the gross lift-off weight to variations in tank weight.

In light of the wide variations noted in this study, the growth allowance of 2% used in the Phase C RFP is believed to be an insufficient margin. It is felt that the tank growth allowance be increased to 10%, similar to the booster and orbiter. The contractors' suggestion to oversize the booster propellant tank at the start of design to increase the Shuttle growth allowance is one logical method to increase the probability of achieving the specified payload capability.

9. TRAFFIC ACCOMMODATION ANALYSIS

At the request of the NASA Study 2.3 Technical Director, an analysis was conducted in January 1972 to estimate the percentage of total payload traffic which could be accommodated by the Shuttle in combination with various upper stages as specified by NASA. The payload traffic considered included NASA, non-NASA, and DOD traffic for the period 1979-90. The NASA and non-NASA payload traffic was derived from the then-current Fleming model, plus "STAR" additions. The DOD traffic was based on the August 1971 Option B mission/traffic model. The number of Shuttle flights totaled 722, assuming that payloads were not combined and excluding manned revisits, which could possibly be combined with payload deployment/retrieval missions. The vehicle combinations specified by NASA included the Shuttle operating by itself and in conjunction with the Agena, Centaur and Tug upper stages.

The results of the analysis showed that the Shuttle operating alone accommodates less than one-third of the total traffic (31.9%), emphasizing the need for an upper stage as an integral part of the STS. Addition of the Agena and Centaur stages operated in the expendable mode permits accommodation of 78.4% and 90.4%, respectively, of the total traffic. The Shuttle when operating with the Tug in the recoverable mode accommodates essentially the same percentage of total traffic (90.3%) as when operating with the Centaur stage in the expendable mode. In practice, either the Centaur in an expendable mode or the reusable Tug can capture the total traffic models since minor adjustments to one of the DOD payloads, accounting for 10% of the traffic, are possible.

10. NUCLEAR WASTE DISPOSAL

As part of a predecessor study to Study 2.3, an evaluation was made of the applicability of the Space Shuttle for nuclear waste disposal. The results of this evaluation were summarized in the Study B Final Report, (Reference 6). During Study 2.3, two follow-on tasks were performed: (a) preparation of a draft Statement of Work for a potential contractor study, and (b) reconciliation of Aerospace and North American Rockwell (NR) Shuttle traffic estimates for nuclear waste disposal in the 1980-2000 time period. The objective of the contractor study was to develop data needed by NASA and the AEC to assess the comparative attractiveness of nuclear waste disposal in space relative to other proposed waste disposal or management systems. In the proposed Statement of Work, emphasis was placed on consideration of system safety and economics.

11. HISTORICAL LAUNCH VEHICLE DATA REVIEW

At the request in January 1972 of the NASA Study 2.3 Technical Director, an effort was made to collect data which would provide insight into the distribution between actual spacecraft weight and upper stage weight delivered into low earth orbit by the U.S. over the past decade. The objective of this effort was to provide guidance based on historical precedent in establishing estimates of how much of the projected Shuttle lift capability is allocable to relatively high cost spacecraft and how much is allocable to relatively low cost upper stages and propellants.

It was established that no central national data file exists which provides direct access to the required historical data. As a substitute, an effort was made to identify on a mission-by-mission basis the spacecraft weight and the upper stage, if employed. Using these data, where applicable, the equivalent weight in low earth orbit was calculated. This method has many uncertainties, but it is better than the previous practice of crediting the launch vehicle theoretical payload capability as actual weight delivered into orbit. Weight data were included for civilian launches only, due to the unavailability of required supporting data for DOD launches. Over the past decade, the ratio of spacecraft weight to total weight delivered into low earth orbit was found to be approximately 20% for NASA unmanned missions, 15% for other unmanned civilian missions, and approximately 18% for NASA manned missions. Year-to-year variances precluded the establishment of secular trends.

12. TUG IMPLICATIONS OF MARK I/MARK II SHUTTLE PROGRAM

In support of visits made by Mr. C. Mathews to the European Space Council and the European Launcher Development Organization in late October of 1971, an assessment was made of the potential implications of the Mark I/Mark II Shuttle program on Tug development planning. Two interim program approaches were considered: (1) use of an expendable booster with the Mark II or final orbiter configuration (Option No. 1); and (2) use of a reusable booster with a Mark I or interim orbiter configuration (Option No. 2). For each option, two interim program durations were evaluated: (1) 1979 through mid-1982 (30 months); and (2) 1979 through 1984 (60 months).

Assessment of Option No. 1 indicated that potential payload capture would be very low. The total number of flights would be low due to the high recurring cost of the expendable booster; priority would be given to Shuttle development flights with air-breathing engines in the cargo bay and to manned mission flights. The Option No. 2 interim program presented a more encouraging outlook because of the higher traffic levels possible, i.e., up to 50 flights in a 30-month program, and up to 100 flights in a 60-month program. The actual traffic capture would depend on the Mark I orbiter payload capability, and on the Tug configuration employed. The operational Tug could be developed at the outset and used in an off-loaded configuration, or an interim Tug could be developed using current technology, thereby permitting the technology freeze date for the operational vehicle to be delayed.

13. ELDO PHASE B COST ESTIMATES

In February 1972, at the request of the NASA Study 2.3 Technical Director, preliminary estimates were made of the tasks which would be appropriate for an ELDO Tug Phase B study effort and also of the associated manhours and costs. It was estimated that the systems Phase B effort would require a total effort of 80 man years per contractor over a period of 12-15 months. The primary engine effort for the same time period was estimated to be approximately 70 man years, plus an allocation of the European equivalent of $1 M US dollars for testing.

C. SUBTASK 2.3.3 - ADVANCED DEVELOPMENT ANALYSIS

The objective of this task was to identify new concepts and techniques which could significantly influence NASA's advanced mission capabilities. It was believed that The Aerospace Corporation's involvement with DOD programs plus company-sponsored research, in addition to work performed in support of the NASA, would provide greater insight into potential advanced development concepts than might normally be possible.

During the course of the study, 37 candidate technology requirements were identified and transmitted to the NASA Subtask Director, Mr. E. W. Hall (Code MTG). The transmittals were made in four bimonthly groups, starting the fourth month of the contract. The distribution of these technology requirements by technical area was as follows:

D	-	Data	3
G	-	Guidance	1
IR	-	Infra-red	1
L	-	Laser Applications	4
M	-	Materials/Structures	6
P	-	Propulsion	2
R	-	Radiometry	2
S	-	Shuttle	3
SB	-	Space Basing	2
T	-	Tug	13

The titles of the 37 candidate technology requirements are given below:

1. Large Screen Display of Detailed Documents/Schematics in Space (D-1)
2. Long-Life, High-Speed Spaceborne Data Preprocessor (D-2)
3. Voice Input to Computer (D-3)
4. Angles-Only Rendezvous Guidance (G-1)
5. High Resolution Far Infra-Red Observations (IR-1)
6. External Power Sources (L-1)
7. High Efficiency Laser For Space-to-Space Communications Systems (L-2)
8. Laser Drilling (L-3)
9. Laser Beam Steering Device for Optical Communication And Ranging Systems (L-4)
10. Lifetime Testing Procedures (M-1)
11. Control or Organic Contaminants (M-3)
12. Survivability (M-3)
13. Structural Life Prediction (M-4)
14. Composite Structures (M-5)
15. Thermodynamics of Metal Carbides (M-6)
16. Space Propellant Decomposition (P-1)
17. Rocket Plume - Surface Interactions (P-2)
18. High Resolution Millimeter-Wave and Submillimeter Wave Radiometers and Radar (R-1)
19. 60 GHz Observation Radar for Earth Orbital Space Stations (R-2)
20. Space Shuttle as a Lunar Rescue Vehicle (S-1)
21. Jet Plume Interaction (S-2)
23. Data Base Requirements for Space-Basing Concepts (SB-1)
24. Zero Gravity Orbital Propellant Transfer Concept (SB-2)
25. Guidance System for Space Vehicles (T-1)

26. Tug LSI Computer (T-2)
27. Tug Software Requirements (T-3)
28. Laser Radar (T-4)
29. Propellant Thermodynamic Studies for Reusable Space Tug (T-5)
30. Auxiliary Propulsion System Study for Space Tug (T-6)
31. Oxygen and Hydrogen Turbopumps for Tug Auxiliary Propulsion System (T-7)
32. Propellant Thermal Conditioning for Tug Auxiliary Propulsion System (T-8)
33. Reaction Control Thrusters for Space Tug Auxiliary Propulsion System (T-9)
34. Tug Reusable Cryogenic Insulation (T-10)
35. Tug Main Rocket Engine Critical Components (T-11)
36. Tug Propellant Oscillation Dynamics (T-12)
37. Tug Propellant Tank Technology (T-13)

D. SUBTASK 2.3.4 - UTILIZATION OF SOLID ROCKET MOTORS FOR SPACE SHUTTLE

The objectives of this study were to convey to NASA the USAF/ Aerospace experience in large solid rocket motor development, to apply this experience to specific analysis for the Shuttle SRM, and to provide parametric and Titan IIIC/D data which are applicable to the Shuttle SRM. To achieve these objectives, the study plan was organized into the following subtasks:

1. SRM Design Analysis
2. SRM Parametric Data Development
3. Special Studies
   (a) SRM Manrating Considerations
   (b) Recovery Systems Concepts
   (c) Titan IIIC/D Experience

The baseline Shuttle configuration and weights were supplied by NASA Marshall Space Flight Center.

1. SOLID ROCKET MOTOR DESIGN ANALYSIS

a. Thrust Negation Response Analysis

This analysis was to determine the loads which will be experienced by the Shuttle when terminating the thrust of the solid rocket motors prematurely for the orbiter abort. Experience gained in the Titan III program indicated that the thrust negation force could be large enough that the interface loads and loading on the vehicle may exceed other design conditions. The tasks included the development of a dynamic model of the Shuttle, analysis of forcing functions (thrust transients) for two thrust negation concepts, and the SRM case response analysis in generating case response loads and SRM/external tank interface loads.

b. SRM Case Structural Design Criteria

The design criteria used for development of the SRM cases for Titan IIIC and Minuteman III were reviewed. Structural design criteria of the SRM case for the Space Shuttle were prepared. The criteria cover major topics such as design requirements, design conditions, and proof of design which included analyses and tests. The development of the document was based on Titan IIIC and other systems experience at Aerospace. The special features of this document were the consideration of reusability, fracture control and proof test requirements. The proof and design factors of safety for the solid rocket motor case were established on the basis of the service life requirement (Number of reuses) of the case and the fracture toughness and flaw growth rate of the case material. Proof pressure test after each flight is considered necessary.

c. SRM Case Materials Study

The SRM case materials study started with the screening of a broad spectrum of possible candidate materials listed below:

Steel:	4340, D6aC, 18Ni and 12Ni maraging, HP9-4, HY-150, T-1
Aluminum:	2014, 2024, 2219, 6061, 7075
Titanium:	6Al-4V, 5Al-2.5 Sn

These materials were narrowed down to five candidate materials (HP 9Ni-4Co, 12Ni, 18Ni, HY150 and D6aC) after considering the trade-offs of material characteristics such as fracture toughness, strength, critical flaw size and weight. High cost and high density were also factors in eliminating some materials. Detailed investigation of the five candidate materials was completed. A material matrix table was prepared considering the following factors for each material; (a) material properties, (b) design characteristics - factor of safety, fracture mode, etc., (c) melt process, (d) fabricability - forming, machining, welding, etc., (e) heat treatment, (f) reusability - corrosion resistance, weld repair, etc., (g) nondestructive inspection (NDI), and (h) proof test philosophy.

2. SRM PARAMETRIC DATA DEVELOPMENT

a. SRM Design Envelope

This task was to generate SRM design envelopes for a range of total impulse by a technique employing a third order thrust model developed in conjunction with the T-IIIC and T-IIIM design efforts. The performance subroutine of the large SRM sizing program is used to generate these design envelopes. The design envelope (commonly called pig-pen) offers a pictorial presentation of the relationship among variables such as thrust-to-weight ratio, web action time, maximum dynamic pressure (q_{max}), payload and the ratio of delivered total impulse prior to q_{max}-to-total impulse. The design envelope will also satisfy vehicle constraints such as q_{max}, q at staging, maximum acceleration, etc. By means of thrust-time curve shaping, the design envelope can be used to define an optimum grain design in terms of simplicity of manufacture, and provide an optimum SRM performance for payload improvement or vehicle GLOW reduction.

b. Internal Ballistics

The objective of this task was to demonstrate the trade-offs involved in establishing the internal ballistics of the SRM including the effect of length-to-diameter, port-to-throat ratio, slot flow effects and grain tapers. This effort is derived from the experience gained in the Titan III program. Parametric ballistic calculations were made for the baseline 3.96 m (156 in.) SRM having a propellant load of 694,008 kg (1,530,000 lb). Trade-offs were conducted on motor operating pressure, port-to-throat area ratio, and the number of segments.

c. Nozzle Design Considerations

The particular consideration for this task was to determine if experience has shown problems relative to canting the SRM nozzle. The Titan IIIC/D SRMs have a six deg cant. In addition, because of previous experience, concern has been shown for aft closure insulation erosion effects. An evaluation of a large number of solid rocket motors has provided no substantiation of any nozzle cant problems. Tests have been run for cant angles as high as 11 deg. However, all the motors considered have, in general, classical nozzle configurations. If the nozzle is buried deep in the port area, there may be some concern since flow conditions become difficult to predict and require extensive testing. Significant results were obtained relative to aft closure insulation erosion. An analysis of a large amount of test data has resulted in correlation of erosion rates as a function of several design factors. Utilizing this approach it is now possible to predict with a reasonable degree of confidence the degree of insulation required in the aft closure area near the nozzle.

3. SPECIAL STUDIES

a. SRM Manrating Considerations

Experience has shown that solid rocket motors are inherently more reliable than liquid rocket engines. This is true for the Titan III program and should also hold for the Space Shuttle. However, it should also be recognized that although large SRMs may be more reliable, the existing failure modes associated with the flight environment tend to result in more severe consequences than would be expected with liquid engines. For example, with T-IIIM, only 10% of the ascent abort forcing failures occur during the SRM flight phase. However, these failures account for 70% of the estimated crew loss.

The failure modes and their subsequent effects determined for the Titan III SRM are directly applicable to the Shuttle. Potential leakage paths exist wherever sections are joined together. Since the O-ring installation is blind, there is the possibility of undetected damage contributing to a leakage path. Further protection is afforded by filling the boot area with potting compound, contributing to a slight loss in performance due to the increased weight, approximately 295 kg (650 lb). Several alternatives were investigated early in the SRM development to reduce the burnthrough potential but were dismissed in favor of stringent controls over the fabrication and assembly process.

Further study of sensing techniques should be employed to improve warning time. New development in ultraviolet sensors may be able to sense impending burnthrough conditions with sufficient warning time to allow thrust negation to be employed, thereby reducing the chamber pressure such that burnthrough is precluded. This is particularly important in the region next to the drop tank. Redundant O-rings offer some improvement in reducing gas leakage but, as blind installations are employed, the potential exists for undetected damage.

b. Recovery Systems Concepts

Several feasible recovery concepts evolved from a study of SRM recovery. All concepts utilize a cluster of parachutes for the final stage decelerator. The systems vary in the type and deployment of the initial decelerator. If a low risk approach is favored, combined with the utilization of devices within the state-of-the-art, an attached inflatable decelerator (AID) offers a viable solution. A substantial weight saving can be obtained if by some, yet undefined, means the SRM is forced into a broadside entry into the atmosphere. This would allow the deployment of the cluster of main chutes (by means of a mortar ejected pilot chute) at considerable less severe conditions than in the first concept.

4. TITAN IIIC/D EXPERIENCE

The experience gained from developing the Titan III Solid Rocket Motors was utilized throughout the total study effort. However, there are five subtasks identified in the Statement of Work which asked for specific data from the Titan III program. These tasks are discussed below.

a. Separation Techniques

This task included reviewing all of the Titan III experience in the area of SRM staging and separation with justification for the final selection given. The staging sequence is presented along with profiles of the solid rocket motors as they fall away from the center core. The application of the Titan III staging and separation experience is implicit. The Shuttle configuration is very similar to the Titan III configuration with the single exception that the core engines (orbiter engines) are burning simultaneously with the solid rocket motors. While this introduces a much different thermodynamic environment in the aft end of the vehicle, the basic staging and separation concepts should be identical for all practical purposes.

b. Plume Impingement Effects

This task considered the impact of using staging rockets to affect separation of the large SRMs from the orbiter/drop tank. This effort is based on the experience gained in the Titan III program. The primary effects are the particle impingement heating and the impingement pressure. The two sizes of staging motors were analyzed, a 8,900 N (2,000 lb) thrust motor supplied in the baseline definition, and a 311,360 N (70,000 lb) thrust motor subsequently defined. Impingement upon the drop tank appears to present no serious problem in that sufficient insulation can be provided. The staging rockets are canted 45 deg from the plane of symmetry and therefore do not directly impact on the tank. However, the aft rockets do impinge on the lower surface of the orbiter wing. The results of the 8,900 N thrust rockets are not particularly severe although some protection may be required. However, the 311,360 N thrust motors result in severe heating. In addition, the impingement pressures exceed $62,224 N/m^2$ (1,300 psf). If these large motors are used, they will undoubtedly present a severe design problem. Although proper placement of the rockets could provide some alleviation, there will probably be little relief because three to four staging rockets are being considered. There is no location where each can be installed without at least one impacting on the orbiter or the drop tank. As a result, further consideration should be given to the staging requirements.

c. Pad Test Environment

In the area of pad test environment, the Titan III experience with regard to the acoustic environment, thermal environment and overpressure environment was reviewed for application to the Space Shuttle. The overpressure design requirements were established by analysis, particularly as applicable to the flame deflector and exhaust duct. The use of protective coatings to minimize refurbishment in the launch area is presented for its direct application to the Space Shuttle.

d. Thrust Vector Alignment

A comprehensive review of the Titan III experience in the area of thrust vector misalignment was conducted for the primary purpose of establishing its applicability to the solid rocket motors being used on the Space Shuttle. It was concluded that the geometric alignment error of the solid rocket motor nozzle to the vehicle can be reduced to zero for all practical purposes. This is accomplished by maintaining very small errors in actual hardware dimensionality and by further adjustments of the solid rocket motor and vehicle alignments on the launch pad. The error of the geometric thrust alignment, as compared to the actual thrust vector alignment, is somewhat questionable. There is some indication that the gas dynamic effects may introduce an error into the actual thrust vector. No conclusive evidence was established on Titan III, primarily because thrust vector control was available to compensate for such an error. It is recommended that this effort be pursued in the Shuttle application to get a better understanding of the actual thrust vector. Another of the thrust misalignment considerations is the differential thrust error as determined by the variations in motor-to-motor ballistics. Considerable data has been evaluated to establish realistic maximum thrust differentials between motor pairs.

e. Vendor Survey

A vendor survey was conducted to determine the availability of solid rocket motor components in the 156 in. size and larger. A review was conducted of Titan III vendor history and the problems encountered to determine application to the Shuttle solid rocket motor; a listing of potential vendors for the Shuttle solid rocket motor was developed. The overall conclusions indicate that qualified vendors are available for all large SRM components. While potential problems do exist, they do not appear severe, but time should be allowed for vendor qualification. New tooling and/or additional facilities will be required as a function of motor size and rate. Additional in-depth studies should be conducted to evaluate motor sizes larger than can be conventionally transported in addition to further studies relative to high production rates.

VI. STUDY LIMITATIONS

The Aerospace Corporation STS Cost Methodology (Reference 2) was used extensively throughout the Study 2.3 effort and exerted a major influence on the conclusions reached in the various study activities. This methodology, developed in FY 1970 under joint DOD/NASA funding, is based on the concept that the cost of a space vehicle and its parts can be shown to be a function of one or more design, performance, or program variables. The credibility and accuracy of any estimate derived through use of the methodology are necessarily functions of the appropriateness of the correlation of costs to the independent variable(s) and the quality of the data upon which the estimate is based.

The cost methodology presently utilizes cost estimating relationships (CERs) which relate costs principally to system and subsystem weights, although there are some major exceptions, e.g., main propulsion. The appropriateness of weight as the major independent variable is open to question in certain of the subsystem areas, e.g., avionics, command and control, etc., although more appropriate independent variables are not immediately apparent. Continued development of the methodology in these areas is clearly in order.

Many of the study activities reported in this summary were quick reaction in nature and took advantage of existing vehicle and programmatic data. In some cases, these data were not entirely self-consistent and may have yielded study results which would be modified by a more comprehensive study program. It is not expected, however, that the principal conclusions drawn in the various study activities would be materially altered.

VII. IMPLICATIONS FOR RESEARCH

The activities reported herein were oriented primarily towards systems analysis and did not investigate research opportunities, *per se*. However, the potential for research was noted in two areas: (a) cost estimating methodologies and (b) advanced development concepts.

The various Study 2.3 activities have reconfirmed the often-made point that cost data are of equal importance to technical data in the formulation of major space program decisions. However, historically the resources expended to insure that the cost data are credible have been only a small fraction of the resources expended in the technical areas. A comprehensive cost data research program which identifies, relationalizes, and correlates space-related cost data would yield substantial benefits in future program planning.

Thirty-seven potential candidates for advanced development were identified under Subtask 2.3.3, Advanced Development Analysis. Any of these candidates which are found worthy of further effort by NASA would entail either research or development or, in some cases, both. Because of the diversified nature of these candidate concepts, no specific comments can be made regarding specific research and/or development activities which should be pursued by NASA.

VIII. SUGGESTED ADDITIONAL EFFORT

The most important area in which additional effort is suggested is the continued refinement and enhancement of the planning tools used in Study 2.3. These tools comprise principally The Aerospace Corporation STS Cost Methodology and, to a lesser extent, The Aerospace Corporation Weight Synthesis Computer Program. As noted in the Section VI discussion of cost methodology, a closer relationship is needed between the independent variable used for subsystem cost estimating and the principal subsystem function. In addition, the data base from which the Cost Estimating Relationships are derived should be updated and expanded to include all applicable experience, especially in the area of solid rocket motors (SRMs).

IX. APPENDIX A

STUDY 2.3 STATEMENT OF WORK

2.3 ANALYSIS OF ADVANCED PROGRAMS

2.3.1 Vehicle Data Reference Base

The contractor shall build on the information developed under paragraph 2.1 above and shall maintain a data bank which relates vehicle descriptions, performance, cost, and technical risk for configurations under review.

The contractor shall update and refine computer programs and methodology used by him to estimate program cost implications of space vehicle program uncertainties. Specifically included are the contractor's vehicle synthesis program and his cost estimating program, both of which were developed under DOD/NASA funding in previous years.

The vehicle synthesis program shall be modified to be more specifically adapted to current Space Shuttle configurations which involve new stage concepts and greater use of expendable stages and hardware than had been anticipated when the model was formulated. Specifically to be included are the capabilities to assess drop tank orbiter vehicles, orbiter vehicles employing expendable thermal protection systems, Mark I/Mark II orbiter vehicles, heat-sink boosters, non-flyback recoverable boosters, and pressure-fed boosters, both single and dual. The contractor shall also modify the output format of the vehicle synthesis program to be more compatible with the data input format requirements of the NASA-MSC costing program. In addition, the contractor shall refine and update weight estimating relationships developed in the vehicle synthesis program to be more responsive to variations in total vehicle weight and size. Of specific interest are the weight estimating relationships related to the subsystems such as the hydraulic and the electrical subsystems, including power, power distribution, and auxiliary power units. The specific schedule for accomplishment of the modifications identified above shall be coordinated with the NASA Technical Director and with NASA-MSC personnel as specified by the Technical Director.

The cost estimating program shall be updated to reflect the results of recently completed NASA-sponsored vehicle data studies. The contractor shall review the results of the data studies and compare these results with the data used in the initial formulation of the contractor's cost estimating relationships (CERs). Where differences exist, the contractor shall (a) update the CER in question or (b) develop a rationale as to why the CER should not be updated in view of the later data. Of immediate concern are the contractor's CERs pertaining to body and tank structure and aerodynamic surfaces. The contractor shall also review his CERs related to spares, subsystems and current support equipment and identify corrective actions.

2.3.2 Advanced STS Program Analysis

Using the data compiled under paragraph 2.3.1 above, the contractor shall analyze the relative effectiveness of advanced STS programs identified by NASA. The effort shall include consolidation of technical, economic and programmatic factors, such as development schedules, growth potential, and sensitivity to program changes. The contractor shall include analysis of the impact of the alternative programs on DOD mission and program objectives. In addition, the contractor shall analyze the impact of DOD plans on NASA programs.

This analysis of advanced STS programs will suggest potential benefits which might be gained either through novel and imaginative application of vehicle configurations presently under study or through development of new vehicle configurations. The contractor shall conduct conceptual design/analysis activities in sufficient depth to establish first-order verification of the hypothesized program benefit and to report to NASA the resulting vehicle implications.

During the conduct of the vehicle and program analyses under this contract the contractor will encounter technical or economic uncertainties which require the conduct of advanced program studies for resolution.

The contractor shall define the nature of the problem area and shall prepare supporting documentation to define and describe the required study effort.

The contractor shall advise the Technical Director of the need for recommended study changes or for additional studies by letter as soon as these needs are identified. The contractor shall provide to the Technical Director a program assessment thirty days after each of three major program milestones and in his final report. These milestones and their currently scheduled data of accomplishment are: (a) vehicle configuration selection - 15 December 1971; (b) final contractor data dump - 28 February 1972; and (c) RFQ release - 1 June 1972.

2.3.3 Advanced Development Analysis

During the conduct of STS-related studies at The Aerospace Corporation that relate to both NASA and DOD new concepts and techniques are identified which could significantly influence advanced mission capabilities. In many cases evaluation and exploitation of the full potential of these new concepts and techniques requires the conduct of advanced development programs.

The objective of this activity is to develop and maintain a descriptive catalog of the identified development requirements. Primary emphasis shall be placed on "space systems," i.e., those space development activities which are applicable to multiple programs and not assignable as unique to, for instance, Space Shuttle development requirements. Typical examples of this category of tasks are aerobraking, energy storage systems, special laser developments, lunar surface oxygen production and storage, abort and rescue systems, liquid transfer, etc.

The content of current related OART advanced technology programs, OMSF advanced studies and on-going programs and, where security regulations permit, DOD programs shall be reviewed and evaluated for applicability to the candidate development requirements. Based on this review, technical summaries shall be prepared which describe where future OMSF development activities could be applied to contribute to the advancement of "space systems" concepts and techniques. These technical summaries shall be prepared in a format which is compatible with Research and Technology Operating Plans (RTOP) requirements and shall be submitted to provide maximum benefit to budgetary planning activities.

The contractor shall review with NASA-Headquarters personnel as identified by the Technical Director the current content of his catalog of advanced development opportunities and shall identify those of particular interest every two months, commencing in the fourth month of the study.

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4. SRM Cost Model, ATR-73(7313-01)-4, The Aerospace Corporation (15 September 1972)

5. Aerospace Vehicle Synthesis Program, ATR-73(7313-01)-5, The Aerospace Corporation (September 1972)

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C. Davenport
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G. M. Forslund
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L. R. Sitney (6)
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